Re-analysis of the $(J = 5)$ state at $592\,\mathrm{keV}$ in ^{180}Ta and its role in the ν-process nucleosynthesis of ^{180}Ta in supernovae

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Abstract

We analyze the production and freeze-out of the isomer $^{180}\text{Ta}^m$ in the ν-process. We consider the influence of a possible low-lying intermediate ($J = 5$) state at $592\,\text{keV}$ using a transition width estimated from the measured half-life. This more realistic width is much smaller than the previous estimate. We find that the $592\,\text{keV}$ state leads only to a small reduction of the residual isomer population ratio from the previous result; i.e., considering this better estimate for the transition width, the isomer population ratio changes from $\mathcal{R} = 0.39$ to $\mathcal{R} = 0.38$, whereas previously it was estimated that this transition could reduce the ratio to $\mathcal{R} = 0.18$. This finding strengthens the evidence that ^{138}La and ^{180}Ta are coproduced by neutrino nucleosynthesis with an electron neutrino temperature of $kT \approx 4\,\text{MeV}$.

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The possible astrophysical origin of the rarest isotope in Nature, $^{180}\mathrm{Ta}^m$, has been speculated upon for the last 30 years [1–4]. The problem with this isotope lies in the fact that it is bypassed in the normal nucleosynthesis processes for heavy nuclei. The most promising production scenario in recent times involves neutrino-induced reactions on $^{180}\mathrm{Hf}$ and $^{181}\mathrm{Ta}$ during core-collapse supernovae (i.e. the ν process) [4–6]. However, previous calculations could not satisfactorily explain the solar abundance of $^{180}\mathrm{Ta}^m$ relative to $^{16}\mathrm{O}$ (or $^{24}\mathrm{Mg}$) because they lacked a realistic calculation of the residual population ratio of the isomer to the true ground state. Knowing this ratio is crucial because the true ground state decays with a lifetime of only $8.15\,h$, while the naturally occurring state is $^{180}\mathrm{Ta}^m$ with a lifetime $> 10^{15}\,y$ (see Fig. 1). The purpose of this paper is to demonstrate that by carefully considering the limits on the lowest possible state which can connect the ground state and the isomer, it is possible to place a much more stringent constraint on the final residual ratio.

In the ν process scenario of interest here $^{180}\mathrm{Ta}$ is produced at relatively high temperatures so that a thermal equilibrium exists between the long-lived high-K 9^- isomer at $77\,\mathrm{keV}$ and the short-lived low-K 1^+ ground state. During freeze-out the high-K states and the low-K states become decoupled because the thermal photon bath is no longer able to populate higher-lying so-called intermediate states (IMSs) which decay to both the low-K and the high-K states of $^{180}\mathrm{Ta}$.

In order to clarify the residual ratio between the ground state and the isomer, in a recent paper [7] we studied the nucleosynthesis of $^{180}\mathrm{Ta}^m$ in the ν-process. The time-dependent evolution of the residual isomeric ratio was carefully followed, see Eqs. (1)–(4) in [7]. Details of this evolution are independent of the production mechanism and are thus also valid for the so-called γ-process that probably occurs in type II supernova explosions [3, 8–10].

In the previous study [7] we utilized experimental values for the transition strengths and integrated cross sections of the known IMSs in $^{180}\mathrm{Ta}$ which have been measured by photoactivation [11, 12]. The resulting isomeric residual population ratio $\mathcal{R} = P_m/(P_g + P_m)$ was found to be $\mathcal{R} = 0.39 \pm 0.01$, where the uncertainty was evaluated from the experimental errors of the energy width [12]. This result was an improvement upon an earlier determination [13] of $\mathcal{R} = 0.35 \pm 0.04$ that was obtained from an estimate of the freeze-out temperature without following the time-dependent evolution in detail. We also found that the final result $\mathcal{R} = 0.39 \pm 0.01$ was nearly independent of a number of astrophysical parameters such as the progenitor mass, the supernova explosion energy, the neutrino energy spectrum, or the peak

temperature of the nucleosynthesis environment. This independence arises because ^{180}Ta is completely thermalized in the initial environment where the temperature is high $T_9 > 0.62$ (where T_9 is the temperature in 10^9 K). Also, although the final isomer residual ratio is determined from the time-dependent evolution during freeze out, it is rather insensitive to the time scale for freezeout [7].

It has not been possible until recently to find the IMSs in ^{180}Ta by γ-ray spectroscopy [14–17]. However, the existence of IMSs has now been clearly confirmed by photoactivation experiments (see [11, 12], and earlier experiments referenced therein). The lowest experimentally confirmed IMS is located 1.01 MeV above the 9^- isomer at 77 keV, leading to a total excitation energy of 1087 keV with an uncertainty of about 10 keV. Walker *et al.* [18] pointed out that the excitation energies of the lowest three IMSs (1087, 1297, and 1507 keV) with experimental uncertainties of $10 - 30$ keV [11, 12] are "very close" to the energies of three states which were measured by γ-ray spectroscopy experiments to be at 1076, 1277, and 1499 keV. The three excited states observed by the γ-ray spectroscopy are members of a rotational band, whose band head is located at 592 keV.

This 592-keV state predominantly decays to a 4^+ state at 520 keV with a measured half-life of $T_{1/2} = 16.1 \pm 1.9$ ns. It was suggested that the 592-keV state may decay to the 7^+ state at 357 keV on the high-K side via a K-allowed 235-keV γ-ray (see Fig. 1) [13]. This state cannot be detected in photoactivation experiments because there is no direct branch from the 592 keV state to the 9^- isomer. We estimated the transition width of this state in our previous paper [7] using an exponential extrapolation (see Fig. 4 in [7]). In this way we inferred a transition width of $\Gamma_{\mathrm{tr}} = (g_{\mathrm{IMS}}/g_{\mathrm{iso}})\Gamma_{\mathrm{iso}} = 3 \times 10^{-6}$ eV. This leads to a significantly different isomer ratio of $\mathcal{R} = 0.18$ instead of $\mathcal{R} = 0.39$. However, since there is no experimental evidence suggesting the existence a transition to the IMS at 592 keV, this smaller $\mathcal{R}$ was not adopted in [7]. A transition width of $\Gamma_{\mathrm{tr}} = 3 \times 10^{-6}$ eV would imply a lifetime for this state of $T_{1/2} < 0.15$ ns. However, as seen from Fig. 1, this state has a much longer measured half-life of $T_{1/2} = 16 \pm 1.6$ ns even if 100% of the decay of this state is via the $E2$ transition, implying that our previous estimate of the width for this state was an overestimate by more than two orders of magnitude.

A small transition width of $\Gamma_{\mathrm{tr}} = 1.6 \times 10^{-10}$ eV for the 235-keV γ-ray was estimated with an assumption of the 1% branch for this γ-ray and the measured half-life of the 592-keV state [13]. This corresponds to 7.5×10^{-3} Weisskopf units (W.u.) Based upon these

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arguments, we have repeated our calculation of the time-dependent freeze-out of ^{180}Ta using the more realistic much smaller estimate for the transition width of $\Gamma_{tr} = 1.6 \times 10^{-10}$ eV for the 592 keV state [13]. The resulting isomeric ratio is $\mathcal{R} = 0.38$, quite close to the value $\mathcal{R} = 0.39$ calculated from the experimentally known IMSs, but much larger than $\mathcal{R} = 0.18$ based upon the previous unrealistically large extrapolated width of $\Gamma_{tr} = 3 \times 10^{-6}$ eV. This result is not surprising. The transition rates λ^* between high-K and low-K states in ^{180}Ta of the 1087 keV state (experimentally confirmed) and of the 592 keV (using the above estimated transition width) state are almost identical in the freeze-out temperature region (see Fig. 2).

The parity assignment of the 592-keV state is critical for the existence of the 235-keV transition. Although a 5^+ assignment for 592 keV state is favored, the parity has not been experimentally established [19]. In the case of a 5^- assignment, again an E2 transition to the high-K side with $\Delta K = 2$ to the 7^- state at 463 keV is possible. However, the estimated transition strength may be somewhat lower than in the case of the 5^+ assignment because of the smaller transition energy; this finally leads to isomeric ratios between $\mathcal{R} = 0.38$ and 0.39. The influence of the 592 keV state on the isomer residual ratio $\mathcal{R}$ remains negligibly small under any conditions.

Many γ-ray spectroscopy experiments [14–17] have been carried out but the 235-keV γ-ray or other decay branches of the 592 keV state have not yet been detected. These transitions may be strongly hindered. Such hindrances are certainly expected when there are configuration changes such as a change of both neutron and proton orbitals [20]. In fact large hindrance factors of 10^{-2}–10^{-6} W.u. have been measured for the K-allowed transitions in ^{180}Ta [15]. If it were experimentally confirmed that the upper limit of the decay branches is less than 1%, this would be evidence supporting the ν process origin of ^{180}Ta. In the s process, the 592 keV state will be the most important IMS at temperatures around $kT \approx 23$ keV. If the decay branches are experimentally confirmed, the effective half-life of ^{180}Ta decreases drastically and the survival of ^{180}Ta in the s process becomes difficult [13]. Therefore a measurement of the weak decay branches of the 592 keV state would be highly desirable although this would be a challenging experiment as in the case of ^{176}Lu [21].

We should also briefly mention that the influence of the surrounding plasma on the nuclear transitions in ^{180}Ta has been studied recently [22]. It was found that within the present knowledge of IMSs the surrounding plasma does not have significant influence on

the nucleosynthesis of ^{180}Ta.

In conclusion, we have taken into account the claimed lowest IMS in ^{180}Ta at $592\,\mathrm{keV}$ for the time-dependent evolution of the isomeric ratio $\mathcal{R}$ in the freeze-out of core-collapse supernova explosions. Using a 5^+ assignment and a more realistic estimate [13] for the transition width, we find that the isomeric ratio decreases slightly from $\mathcal{R} = 0.39$ to $\mathcal{R} = 0.38$ for the nucleosynthesis of ^{180}Ta in γ- and ν-processes in supernova explosions. Another assignment $J^\pi = 5^-$ leads to even smaller modifications of $\mathcal{R}$. Hence, even if the 592-keV state is indeed the lowest IMS in ^{180}Ta, its influence remains negligibly small for the freeze-out in the ν- and γ-processes. The main conclusion of the previous study [7] is thus strengthened: the solar abundances of ^{138}La and ^{180}Ta relative to ^{16}O can be systematically reproduced by neutrino nucleosynthesis and an electron neutrino temperature of $kT \approx 4\,\mathrm{MeV}$.

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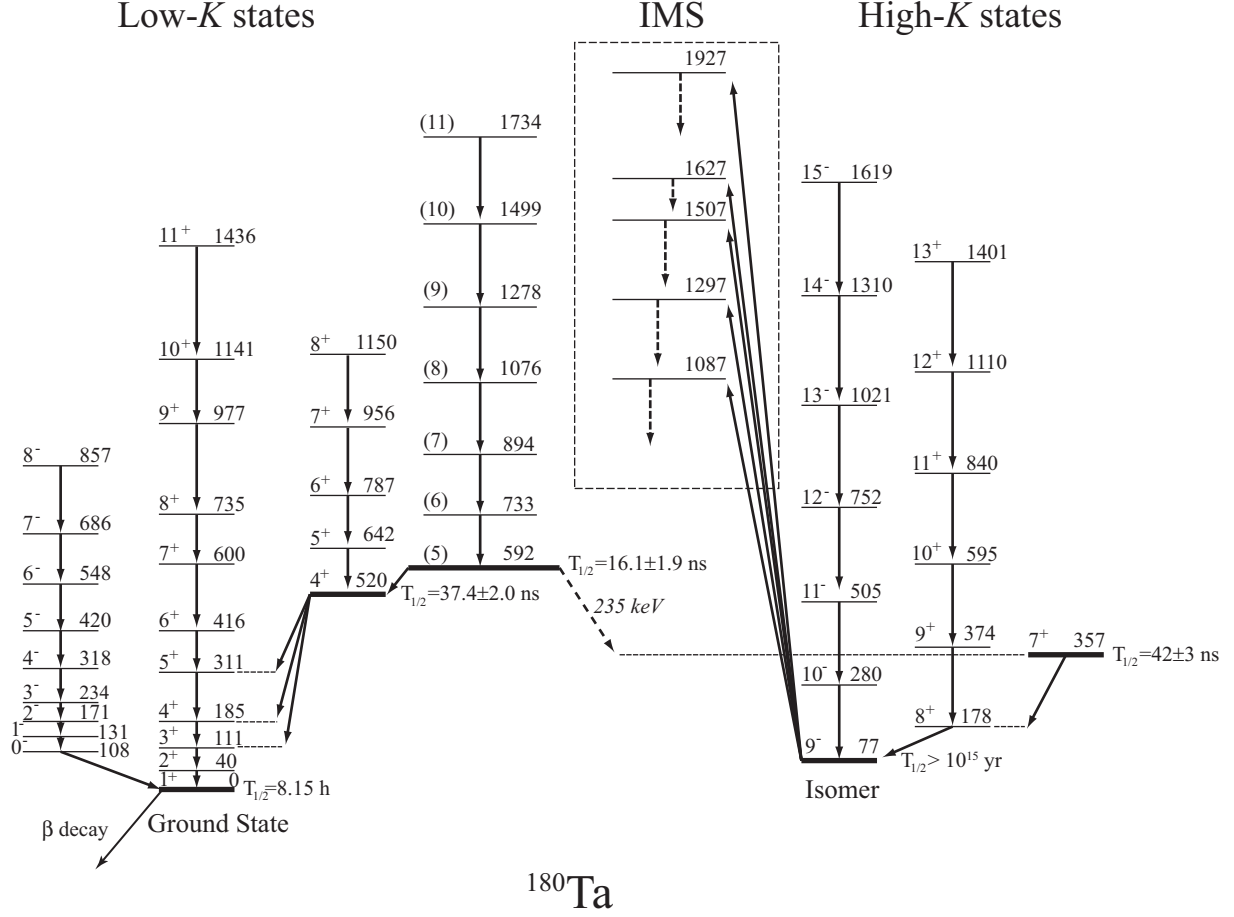[22] G. Gosselin, P. Morel, P. Mohr, Phys. Rev. C **81**, 055808 (2010).

FIG. 1: Partial level scheme of ^{180}Ta. The excitation energies, spins, and parities of most levels are taken from the evaluated data [19]. The excitation energies of ($J = 5$) band are taken from Refs. [14, 15].
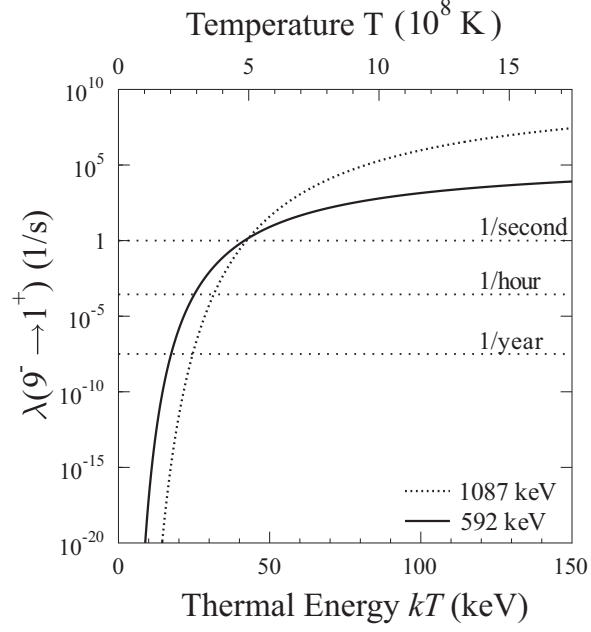
FIG. 2: Reaction rates λ^* under stellar conditions for the transition from the high-K isomer to the low-K ground state in ^{180}Ta. Lines on this figure show contributions from the experimentally confirmed IMS at $1087\,\text{keV}$ (dotted line) and the suggested IMS at $592\,\text{keV}$ (solid line). The relevant freeze-out region is between $4.4 \leq T_8 \leq 6.2$ where T_8 is the temperature in $10^8\,\text{K}$.